VOL. 11, NO. 8, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
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LOW FREQUENCY MICRO-ELECTRO-MECHANICAL SYSTEM (MEMS)-BASED PIEZOELECTRIC ENERGY HARVESTER

Salem Saadon [1,2], Yufridin Wahab [1,2], Zul Azhar bin Zahid Jamal [1,2], and Othman Sidek[3]
[1]Advanced Multidisciplinary MEMS Based Integrated Electronics NCER Centre of Excellence
[2]School of Microelectronic Engineering, Universiti Malaysia Perlis, Perlis, Malaysia
[3]School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Malaysia
E-Mail: saadonsalem@yahoo.com

ABSTRACT

The relatively short lifetime of batteries cannot fulfill the requirements for some wireless sensors. This is particularly the case where replacing batteries is difficult, dangerous and expensive. Energy harvesting systems have been proposed as a solution to such problem, In this paper, we proposed a model and presented the simulation of a MEMS-based arrayed energy harvester under ambient vibration excitation using Coventorware approach. This arrayed cantilever-based MEMS piezoelectric energy harvester operated under ambient excitation frequency band of 67 to 70 Hz, within a base acceleration between 0.2 to 1.3g produced an output power and voltage of 6.8 μw and 0.4 volt respectively.

Keywords: piezoelectric materials, energy conversion, micro cantilever.

INTRODUCTION

The flexibility associated with piezoelectric materials makes them very attractive for power harvesting. Piezoelectric materials possess a large amount of mechanical energy that can be converted into electrical energy, and they can withstand large strain magnitude.

Many methods have been reported to improve the harvested power of micro electromechanical systems (MEMS) micro-generators.

One of these methods is the selection of a proper coupling mode of operation, which involves two modes.

The first mode, called 31mode, considers the excited vibration force being applied perpendicular to the poling direction (pending beam). The other mode is called the 33mode in which the force is applied on the same side as the poling direction. Between the two modes, the 31mode is the most commonly used, which produces a lower coupling coefficient “k” than the 33mode.

The second method to improve harvested power requires changing the device configuration, accomplished by adding multiple piezoelectric materials to the harvester.

The unimorph cantilever beam configuration proposed by Johnson *et al*. (2006) demonstrated that, a highest power could be generated using this configuration under lower excitation frequencies and load resistance.

Two combinations of the bimorph structures are possible, namely, the series and the parallel types. Series and parallel triple-layer bimorph structures were presented by Ng and Liao(2004, 2005). The series triple-layer bimorph was made of a metallic layer sandwiched between two piezoelectric materials, and the piezoelectric patches were electrically connected in series. For the parallel triple-layer bimorph, which was also sandwiched between two piezoelectric layer bimorphs, the piezoelectric materials were connected in parallel.

The parallel triple-layer bimorph generates the highest power under medium excited frequencies and load resistance, whereas the series triple-layer bimorph produces the highest power when excited under higher frequencies and load resistance. The series connection method will increases the device impedance as well as improve the delivered output power at higher loads.

Several researchers have carried out studies to improve the bimorph efficiency. Jiang *et al*. (2005) investigated a bimorph cantilever with a proof mass attached to its tip.

Their results showed that reducing the bimorph thickness and increasing the attached proof mass decreased the harvester resonant frequency and produced a maximum harvested power. Similarly, Anderson and Sexton (2006) found that varying the length and width of the proof mass affected the output of the harvested power. The cantilever geometrical structure also plays an important role in improving the harvester’s efficiency.

Rectangular-shaped cantilever structures are most commonly used in MEMS-based piezoelectric harvesters. They are easy to implement and effective in harvesting energy from ambient vibrations, as proposed in the review paper by Saadon and Sidek (2011). However, the study conducted by Mateu and Moll (2005) showed that a triangular-shaped cantilever beam with a small free end can withstand higher strains and allows maximum deflections, resulting in higher power output compared with the rectangular beam with the width and length equal to the base and height of the corresponding triangular cantilever beam.

Roundy *et al*. (2005) discovered that the strain on a trapezoidal-shaped cantilever beam can be more distributed throughout its structure. They also observed that, for the same volume of lead Zirconate Titanate (PZT), the trapezoidal cantilever beam can deliver more than twice the energy than the rectangular-shaped beam can. Similarly, Baker *et al*. (2005) experimentally tested a nearly triangular trapezoidal-shaped cantilever beam, along with a rectangular-shaped beam of the same volume. They found that 30% more power could be

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achieved using the trapezoidal beam than that using the rectangular one.

Another method of improving the efficiency of a power harvester is by tuning the device so that its resonant frequency matches the ambient vibration-resonant frequency. Shahruz (2006a, b) designed a power harvester that can be resonated at various frequency ranges without the need for any adjustment. This device consisted of different cantilever beams with different lengths and different tip masses attached to its common base frame such that each cantilever has its own resonant frequency. This configuration resulted in a “mechanical band-pass filter,” which led to the increase in size and cost of the device. Rastegar *et al*. (2006) designed a passive tuning system that had a two-stage system in which a very low frequency (0.2 Hz to 0.5 Hz) can be converted into potential energy and then transferred to the system at a higher natural frequency.

Similar works on the modeling, design, fabrication, and simulations of shaped cantilevered structure MEMS-based piezoelectric power harvesters were conducted by other authors (Marzencki *et al*. 2005, 2008; Shen *et al*. 2008; Renaud *et al*. 2008; Fang *et al*. 2006; Liu *et al*. 2008; Jeon *et al*. 2005; Lee *et al*. 2007, 2009; Muralt *et al*. 2009; Elfrink *et al*. 2009; Littrell & Grosh 2012; Lallart *et al*. 2012; Park *et al*. 2010; Liu *et al*. 2011; Wasa *et al*. 2012; Tabesh & Frechette, 2010).

MEMS CANTILEVER-BASED HARVESTER

Materials declaration

The reduction of the natural frequency of the cantilever beams to meet the excitation frequency captured from ambient vibrations, which are normally less than 200 Hz, in this research a MEMS piezoelectric energy harvester that capable to captured an excitation frequency from ambient vibrations surrounding the device was proposed by using SOI substrate instead of standard substrate.

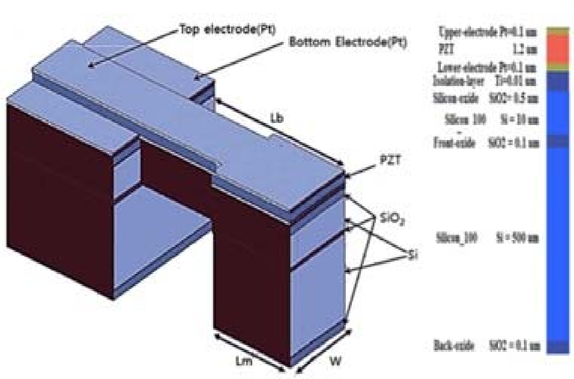

Figure-1. Schematic view of a single cantilever.

It can be found that reduction in the device natural frequency and optimization of the extracted power from environment not only depends upon the volume of the attached proof mass but also on the shape and thickness of the cantilever beam of the device. The harvester model and structure can be shown in Figure-1, while Tables-1 and -2 illustrated the dimensions and the specific properties of the beam materials.

Table-1. Dimensions of the cantilever beam.

Name	Length (µm)	Width (µm)	Thickness (µm)
Beam	2450	450	11.2
Proof mass	1500	780	480

Table-2. Main materials specification.

Materials	Density (kg/µm^3)	Modulus (MPa)	Poisson's ratio
PZT	$7.5x10^{-15}$	$6.2x10^4$	0.25
Silicon	$2.328x10^{-15}$	$1.65x10^5$	0.3

The materials specification of silicon(Si), Silicon dioxide (SiO_2), Lead Zirconate Titanate (PZT), Platinum (Pt.), and Titanium (Ti) were carefully edited in the material editor window of the Coventorware.

Fabrication process

A silicon-on-insulator (SOI) wafer was used in place of more conventional silicon substrates, whereas the buried SiO2 layer added as an etching stop layer. The thicknesses of beam silicon layer, the thermal SiO2 layer and the substrate silicon layer were edited manually to be 10 µm, 100 nm, and 500 µm respectively. A SiO2 layer of thickness about 100 nm was grown on both back and front side of the SOI wafer. The front side SiO2 layer was used to balance the PZT thin film inertial stress then can be performed, and the back oxide was used to mask the area of the surface to prevent damage that may occurred during back-side etching process.

The interlayer Titanium Ti (10 nm) was used as an adhesion (seed) between the bottom electrode Pt. and the oxide layer. Through these steps of the process a multi-layered films (Pt./PZT/Pt./Ti/SiO2) were successfully formed on SOI substrate.

Layout and masking layers

All mask names those previously mentoned on the process editor were could be selected to construct the harvester layout as shown in Figure-2.

In the layout editor window many object shapes can be drown after editing their coordinate points, however every mask layer have its own colour as edited previously in the process editor window.

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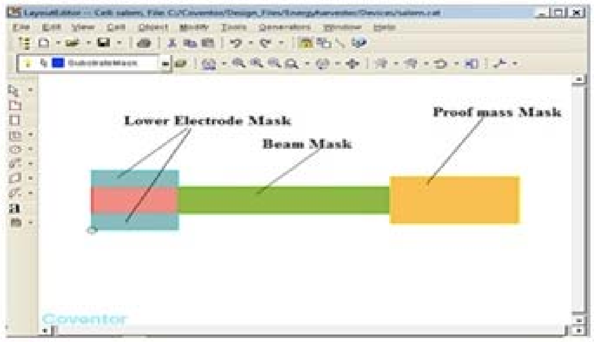

Figure-2. Layout editor window.

Solid and meshed model

The solid model of the device depends upon the previous editors. Precisely edited data were capable to construct the solid or 3-dimensional device. As shown in Figure-3, all the device layers were shown on the left hand side of the processor window.

The developed solid model should be prepared for the simulation process to be achieved, however, the model should be meshed after the mesh element type and size were selected. In this case the Tetrahedrons type mesh with 100-element size had been used.

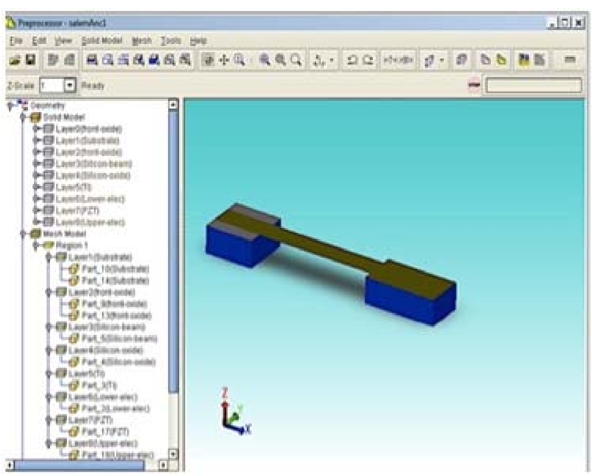

Figure-3. MEMS harvester solid model.

Broadband MEMS energy harvester

Power and voltage optimization of the design harvester has more challenges to overcome the leak power that could be extracted by a single MEMS-based piezoelectric energy harvester, however, micro fabrication of such type of harvesters is complicated and faces more difficulties.

Parallel arrayed broadband energy harvester is more efficient than serial arrayed type in which the extracted power is the same as single type energy harvester. The arrayed parallel type structure is shown in Figure-4.

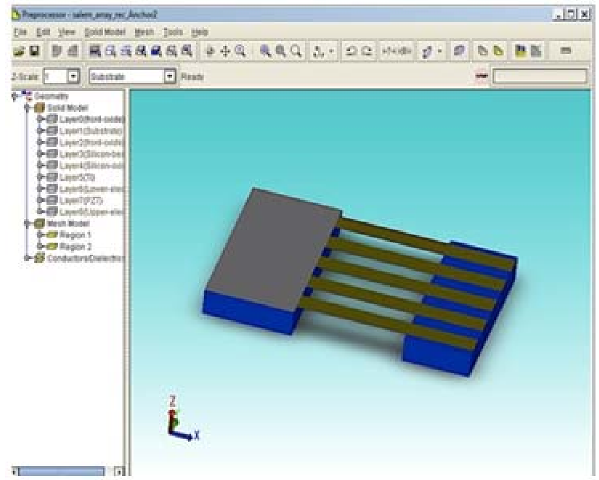

Figure-4. Solid model of arrayed harvester.

ANALYSIS AND RESULTS

Harmonic analysis

According to the results obtained as shown graphically in Figure-5, the cantilever displacement swing between 4200 µm to 6200 µm as shown in Figure-5(a), while the extracted power ranged between 3 µw and 6.8 µw as can be shown in Figure-5(b). However the output voltage fluctuated between 0.25 to 0.4 volts as illustrated in Figure-5(c), whereas the output current ranged from 12 to 18 µA as shown in Figure-5(d).

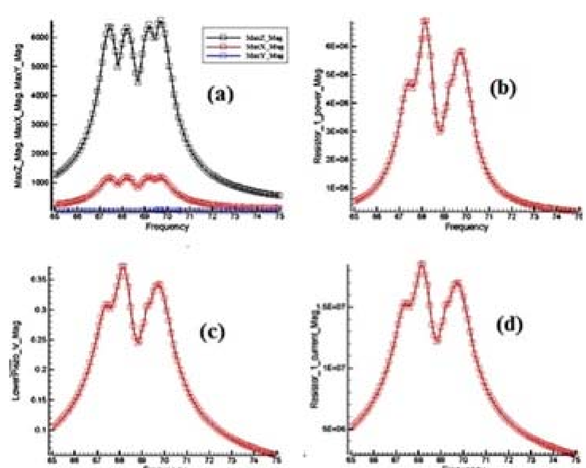

Figure-5. Arrayed harvester output response.

The maximum displacement of the designed broadband harvester is around 6000 micron in Z-direction (vertical displacement), this should be taken into account in order to package the harvester, which means that the height of the package should be not less than 6500 micron to be available at acceleration amplitudes from 0.2 to 1.3 g as shown in Figure-6.

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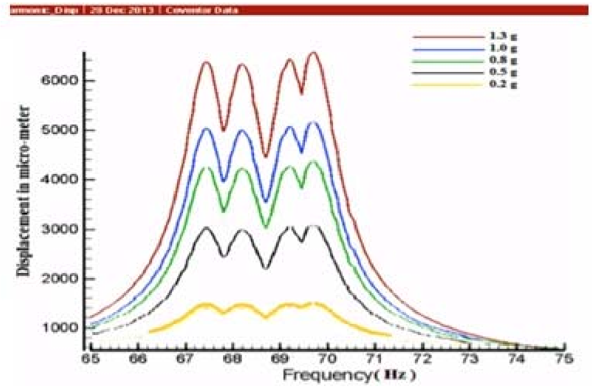

Figure-6. Displacement of arrayed harvester.

Increasing the number of the cantilevers of the harvester will result in wider frequency bandwidth as well as optimization of the output voltage and power (Shahrus 2006 a,b; Liu *et al*. 2008; Hajati & Kim, 2011; Defosseux *et al*. 2011).

The output power and voltage of this proposed broadband energy harvester at different acceleration values (0.2-1.3g) are shown in Figure-7 and Figure-8 respectively.

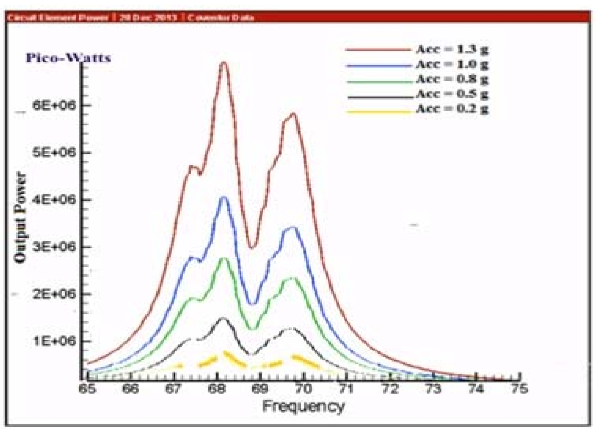

Figure-7. Arrayed harvester output power.

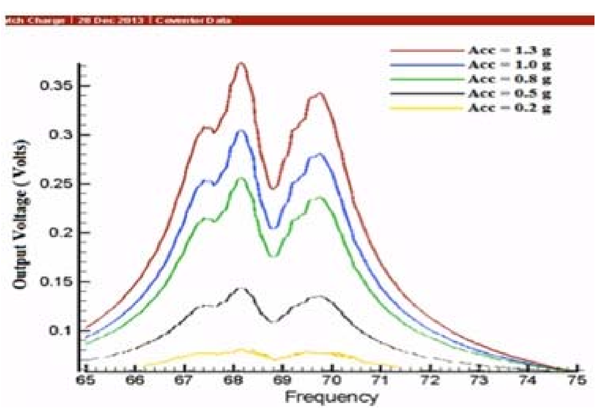

Figure-8. Arrayed harvester output voltage.

Modal analysis

The modal analysis was done by selecting the number of modes in the analyser solver to 5 modes of frequency from 67 Hz to 70 Hz depending upon the excitation frequency band affecting the harvester behaviour.

From Figure-9, each cantilever had its own resonant frequency as indicated by red colours starting from mode1 to mode5 respectively.

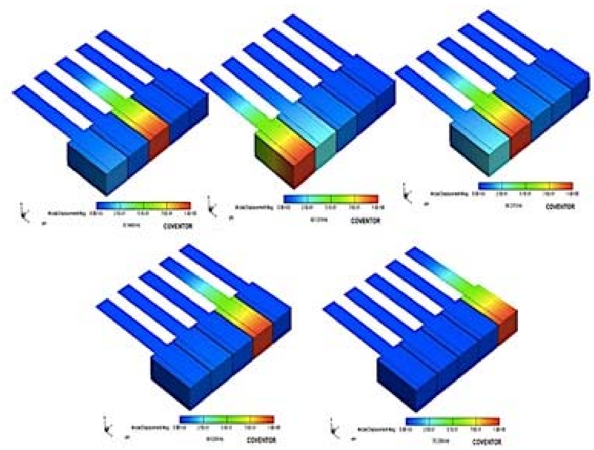

Figure-9. Mode shapes of arrayed harvester.

CONCLUSIONS

Optimization of power, current, and voltage of the designed harvester depends upon the alignment of the layers of the cantilever as well as the thickness of the supporting layer provided that, this thickness should be more than the PZT thickness. As shown in all previously discussed subsections of the single element cantilever that the obtained power is not accounted, while the arrayed 5-element cantilever can generate more voltage and power compared with the single cantilever harvester. Lower frequency response of the harvester could be achieved by the arrayed harvester compared with single harvester constructed from the same element of the cantilever. The results obtained by this Coventorware simulation are closed to the fabrication results of the single element cantilever process done by (Kim *et al*. 2012). However, the fabrication of this arrayed cantilever piezoelectric energy harvester will be the first step in our future work.

REFERENCES

[1] Anderson, T. A., & Sexton, D. W. (2006). A vibration energy harvesting sensor platform for increased industrial efficiency. In Smart structures and materials (pp. 61741Y-61741Y). International Society for Optics and Photonics.

[2] Baker, J., Roundy, S., & Wright, P. (2005). Alternative geometries for increasing power density in vibration energy scavenging for wireless sensor networks. In Proc. 3rd Int. Energy Conversion

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Engineering Conf.(San Francisco, CA, Aug.) (pp. 959-70).

[3] Defosseux, M., Allain, M., Ivaldi, P., Defay, E., & Basrour, S. (2011). Design, fabrication and characterization of wideband piezoelectric energy harvesters?. In International Conference Piezo 2011-Electroceramics for End-users VI (p. pp).

[4] Elfrink, R., Kamel, T. M., Goedbloed, M., Matova, S., Hohlfeld, D., Van Andel, Y., & Van Schaijk, R. (2009). Vibration energy harvesting with aluminum nitride-based piezoelectric devices. Journal of Micromechanics and Microengineering, 19(9), 094005.

[5] Fang, H. B., Liu, J. Q., Xu, Z. Y., Dong, L., Wang, L., Chen, D., & Liu, Y. (2006). Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting. Microelectronics Journal, 37(11), 1280-1284.

[6] Hajati, A., & Kim, S. G. (2011). Ultra-wide bandwidth piezoelectric energy harvesting. Applied Physics Letters, 99(8), 083105.

[7] Jeon, Y. B., Sood, R., Jeong, J. H., & Kim, S. G. (2005). MEMS power generator with transverse mode thin film PZT. Sensors and Actuators A: Physical, 122(1), 16-22.

[8] Jiang, S., Li, X., Guo, S., Hu, Y., Yang, J., & Jiang, Q. (2005). Performance of a piezoelectric bimorph for scavenging vibration energy. Smart Materials and Structures, 14(4), 769.

[9] Johnson, T. J., Charnegie, D., Clark, W. W., Buric, M., & Kusic, G. (2006,). Energy harvesting from mechanical vibrations using piezoelectric cantilever beams. In smart structures and materials (pp. 61690D-61690D). International Society for Optics and Photonics.

[10] Kim, M., Hwang, B., Ham, Y. H., Jeong, J., Min, N. K., & Kwon, K. H. (2012). Design, fabrication, and experimental demonstration of a piezoelectric cantilever for a low resonant frequency microelectromechanical system vibration energy harvester. Journal of Micro/Nanolithography, MEMS, and MOEMS, 11(3), 033009-1.

[11] Lallart, M., Wu, Y. C., & Guyomar, D. (2012). Switching delay effects on nonlinear piezoelectric energy harvesting techniques. Industrial Electronics, IEEE Transactions on, 59(1), 464-472.

[12] Lee, B. S., Lin, S. C., Wu, W. J., Wang, X. Y., Chang, P. Z., & Lee, C. K. (2009). Piezoelectric MEMS generators fabricated with an aerosol deposition PZT thin film. Journal of Micromechanics and Microengineering, 19(6), 065014.

[13] Lee, B. S., Wu, W. J., Shih, W. P., Vasic, D., & Costa, F. (2007). P2E-3 power harvesting using piezoelectric MEMS generator with interdigital electrodes. In Ultrasonics Symposium, 2007. IEEE (pp. 1598-1601). IEEE.

[14] Littrell, R., & Grosh, K. (2012). Modeling and characterization of cantilever-based MEMS piezoelectric sensors and actuators. Microelectromechanical Systems, Journal of, 21(2), 406-413.

[15] Liu, H., Tay, C. J., Quan, C., Kobayashi, T., & Lee, C. (2011). Piezoelectric MEMS energy harvester for low-frequency vibrations with wideband operation range and steadily increased output power. Microelectromechanical Systems, Journal of, 20(5), 1131-1142.

[16] Liu, J. Q., Fang, H. B., Xu, Z. Y., Mao, X. H., Shen, X. C., Chen, D., ... & Cai, B. C. (2008). A MEMS-based piezoelectric power generator array for vibration energy harvesting. Microelectronics Journal, 39(5), 802-806.

[17] Marzencki, M., Ammar, Y., & Basrour, S. (2008). Integrated power harvesting system including a MEMS generator and a power management circuit. Sensors and Actuators A: Physical, 145, 363-370.

[18] Marzencki, M., Basrour, S., Charlot, B., Grasso, A., Colin, M., & Valbin, L. (2005). Design and fabrication of piezoelectric micro power generators for autonomous microsystems. In Proc. of DTIP'05 (pp. 299-302).

[19] Mateu, L., & Moll, F. (2005). Optimum piezoelectric bending beam structures for energy harvesting using shoe inserts. Journal of Intelligent Material Systems and Structures, 16(10), 835-845.

[20] Muralt, P., Marzencki, M., Belgacem, B., Calame, F., & Basrour, S. (2009). Vibration energy harvesting with PZT micro device. Procedia Chemistry, 1(1), 1191-1194.

[21] Ng, T. H., & Liao, W. H. (2004). Feasibility study of a self-powered piezoelectric sensor. In Smart Structures and Materials (pp. 377-388). International Society for Optics and Photonics.

[22] Ng, T. H., & Liao, W. H. (2005). Sensitivity analysis and energy harvesting for a self-powered piezoelectric sensor. Journal of Intelligent Material Systems and Structures, 16(10), 785-797.

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[23] Park, J. C., Park, J. Y., & Lee, Y. P. (2010). Modeling and Characterization of Piezoelectric-Mode MEMS Energy Harvester. Microelectromechanical Systems, Journal of, 19(5), 1215-1222.

[24] Rastegar, J., Pereira, C., & Nguyen, H. L. (2006, March). Piezoelectric-based power sources for harvesting energy from platforms with low-frequency vibration. In Smart Structures and Materials (pp. 617101-617101). International Society for Optics and Photonics.

[25] Renaud, M., Karakaya, K., Sterken, T., Fiorini, P., Van Hoof, C., & Puers, R. (2008). Fabrication, modelling and characterization of MEMS piezoelectric vibration harvesters. Sensors and Actuators A: Physical, 145, 380-386.

[26] Roundy, S., Leland, E. S., Baker, J., Carleton, E., Reilly, E., Lai, E., & Sundararajan, V. (2005). Improving power output for vibration-based energy scavengers. Pervasive Computing, IEEE, 4(1), 28-36.

[27] Saadon, S., & Sidek, O. (2011). A review of vibration-based MEMS piezoelectric energy harvesters. Energy conversion and management, 52(1), 500-504.

[28] Shahruz, S. M. (2006a). Design of mechanical band-pass filters for energy scavenging. Journal of Sound and Vibration, 292(3), 987-998.

[29] Shahruz, S.M. (2006b). Limits of performance of mechanical band-pass filters used in energy scavenging. Journal of sound and vibration, 293(1), 449-461.

[30] Shen, D., Park, J. H., Ajitsaria, J., Choe, S. Y., Wikle III, H. C., & Kim, D. J. (2008). The design, fabrication and evaluation of a MEMS PZT cantilever with an integrated Si proof mass for vibration energy harvesting. Journal of Micromechanics and Microengineering, 18(5), 055017.

[31] Tabesh, A., & Fréchette, L. G. (2010). A low-power stand-alone adaptive circuit for harvesting energy from a piezoelectric micropower generator. Industrial Electronics, IEEE Transactions on, 57(3), 840-849.

[32] Wasa, K., Matsushima, T., Adachi, H., Kanno, I., & Kotera, H. (2012). Thin-film piezoelectric materials for a better energy harvesting MEMS.Microelectromechanical Systems, Journal of, 21(2), 451-457.